Inelastic Dark Matter Around Active Galactic Nuclei

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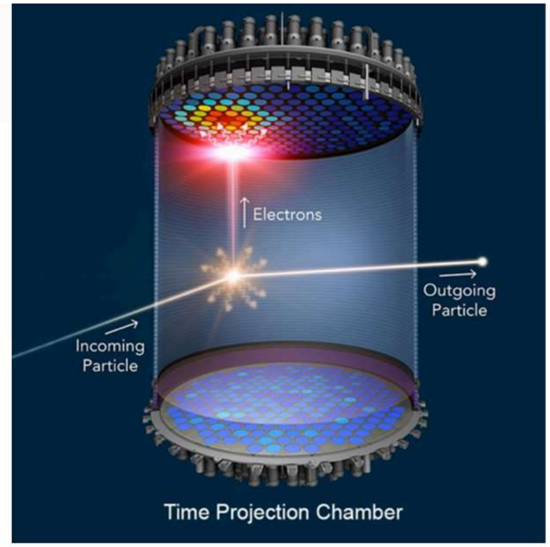
Based on work in 2408.08947 and future works.

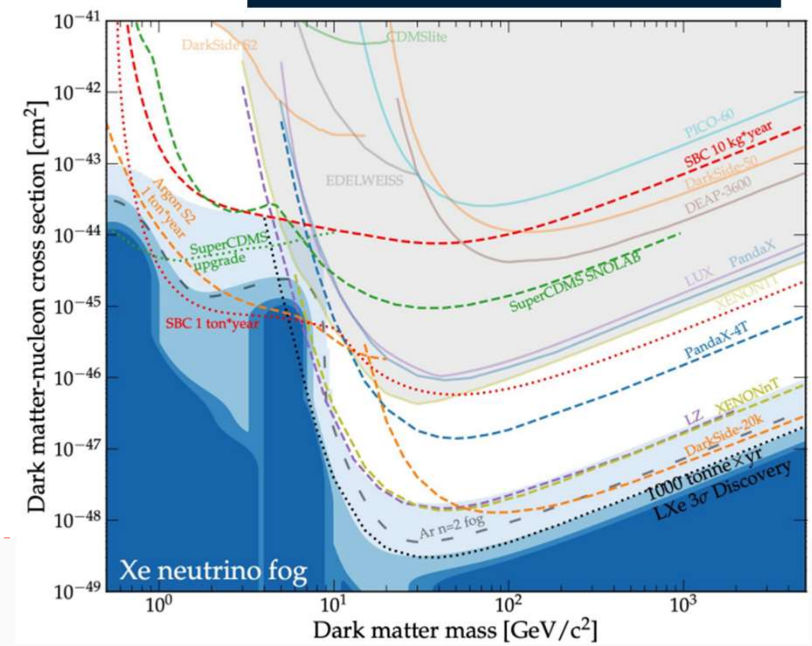
The Center for Neutrino Physics

Introduction



Although the gravitational effects of dark matter (DM) have been observed on galactic and cosmological scales, searches for its particle nature have led to null results. This often is interpreted as DM having very weak couplings to Standard Model (SM) particles.

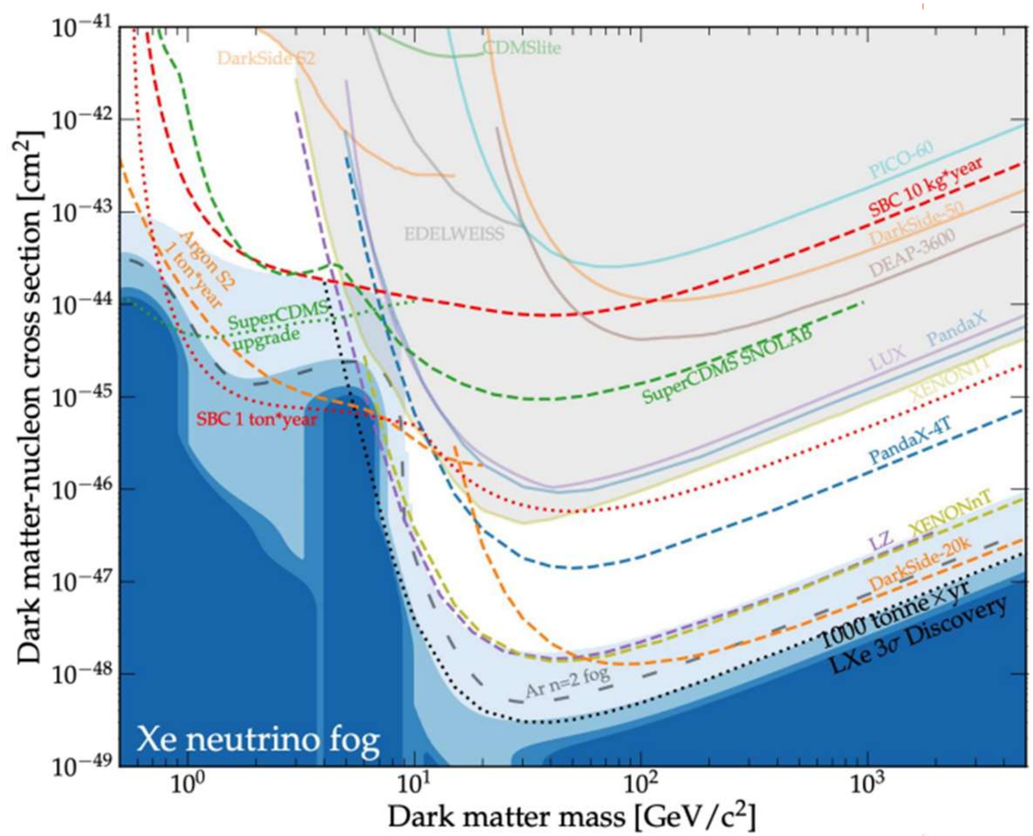
Note that bounds get weaker at low masses. This is because light, non-relativistic DM can not impart enough energy for a visible signal.



([1] Carter Hall, 2024)

Introduction (Cont.)

Taking this idea further, it could be that DM is inelastic, i.e. it must overcome some kinematic threshold to scatter. Then, nonrelativistic virialized DM would not be able to scatter at all in direct detection experiments. Here, we consider Active Galactic Nuclei (AGN) as astrophysical particle accelerators to probe inelastic DM.



([1] Carter Hall, 2024)

Overview

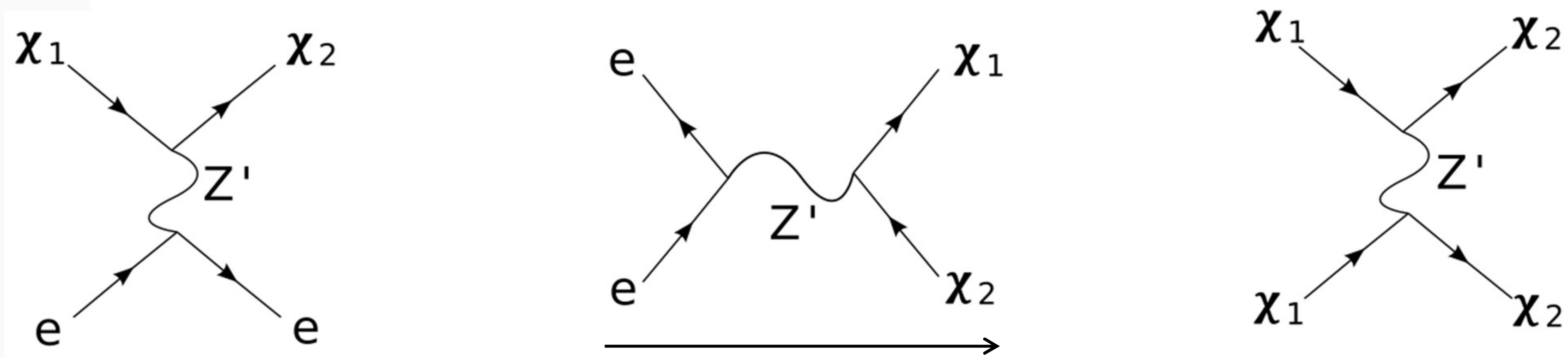
- Inelastic Dark Matter
- AGN Models
- Cosmic Ray Cooling
- Dark Matter Boosting

Inelastic Dark Matter

Model and Interactions

We introduce a ground state fermion χ_1 of mass m_χ, an excited state fermion χ_2 of mass $m_\chi + \delta$, and a vector mediator Z'

$$L_{int} \supset \overline{\chi_1}\left(i\gamma^\mu \partial_\mu - m_\chi\right)\chi_1 + \overline{\chi_2}\left(i\gamma^\mu \partial_\mu - m_\chi - \delta\right)\chi_2$$
$$+ g_\chi \bar{\chi}_1 \gamma^\mu \chi_2 Z'_\mu + (h.c.) + \Sigma_f \, g_{SM,f} \bar{f} \gamma^\mu f Z'_\mu$$

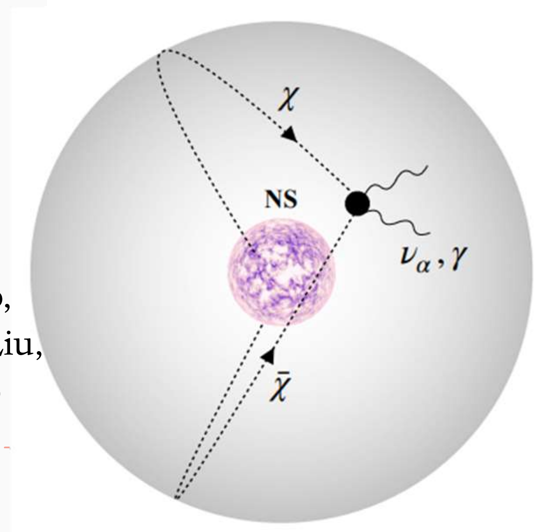


Time

Existing Constraints

Compact Celestial Objects

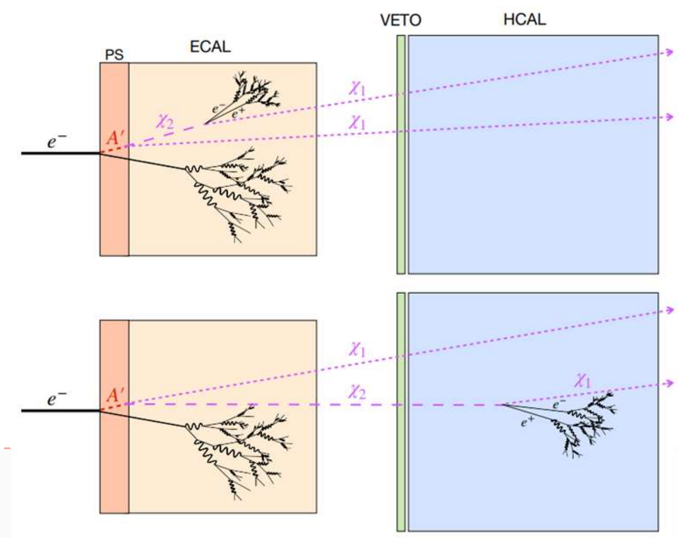
As DM falls onto objects with deep gravitational wells (i.e. white dwarfs or neutron stars) they may obtain enough kinetic energy to scatter



([2] Acevedo, Bramante, Liu, Tyagi, 2024)

Colliders and Beam Dumps

High energy scattering may produce new mediators or excited states, leading to displaced vertices.

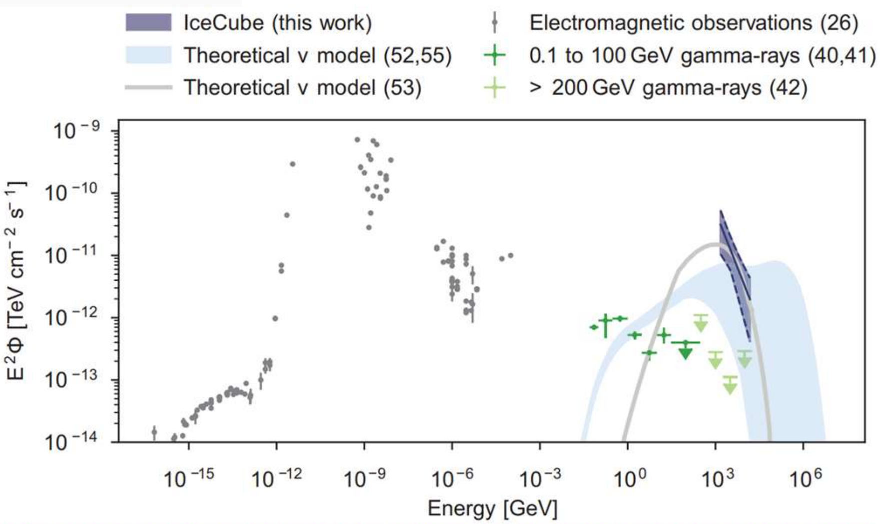


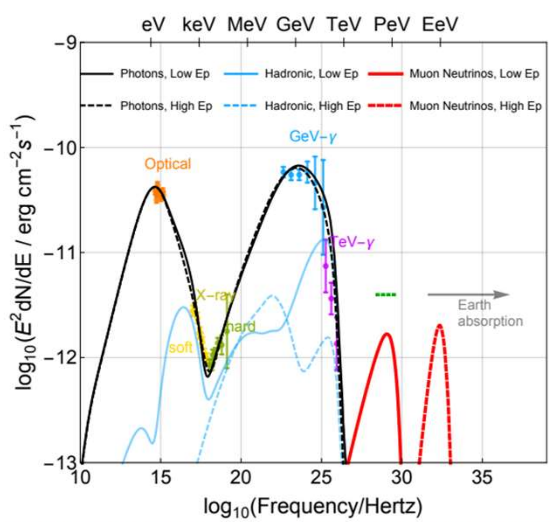
([3] Mongillo et. al. 2023)

Active Galactic Nuclei (AGN)

AGN Observations

AGN are Supermassive Black Holes (SMBH) at the center of galaxies, which have enormous luminosities of boosted particles. AGN have been observed in through electromagnetic signals and high energy neutrino observations.
In this work, we focus on NGC 1068 and TXS 0506+056





NGC 1068
([4]Icecube Collaboration 2022)

TXS 0506+056
([5] Winter et al 2019)

AGN Multimessenger Modeling cont.

For protons in NGC 1068, the primary cooling mechanisms are ([6] Murase 2022):

pp interactions for $T_p \leq 10^4$GeV

$p\gamma$ interactions for $10^4 < T_p \leq 10^6$GeV

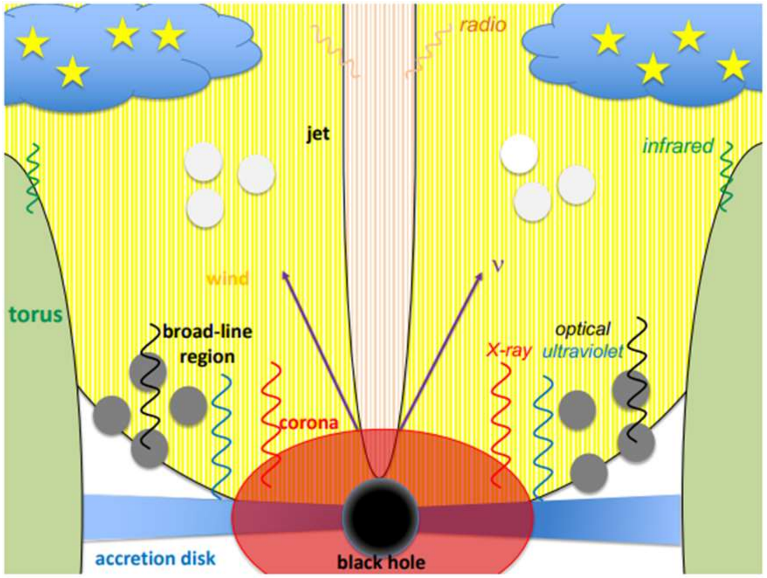
$p\gamma \rightarrow pe^+e^-$ for $T_p > 10^6$GeV

For electrons in TXS 0506+056 ([6] Keivani et al. 2018):

escape losses for $T_e < 5$ GeV

ICS for 5 GeV $< T_e < 40$ GeV

synchrotron radiation for $T_e > 40$ GeV



([6] Murase 2022)

Dark Matter Spike

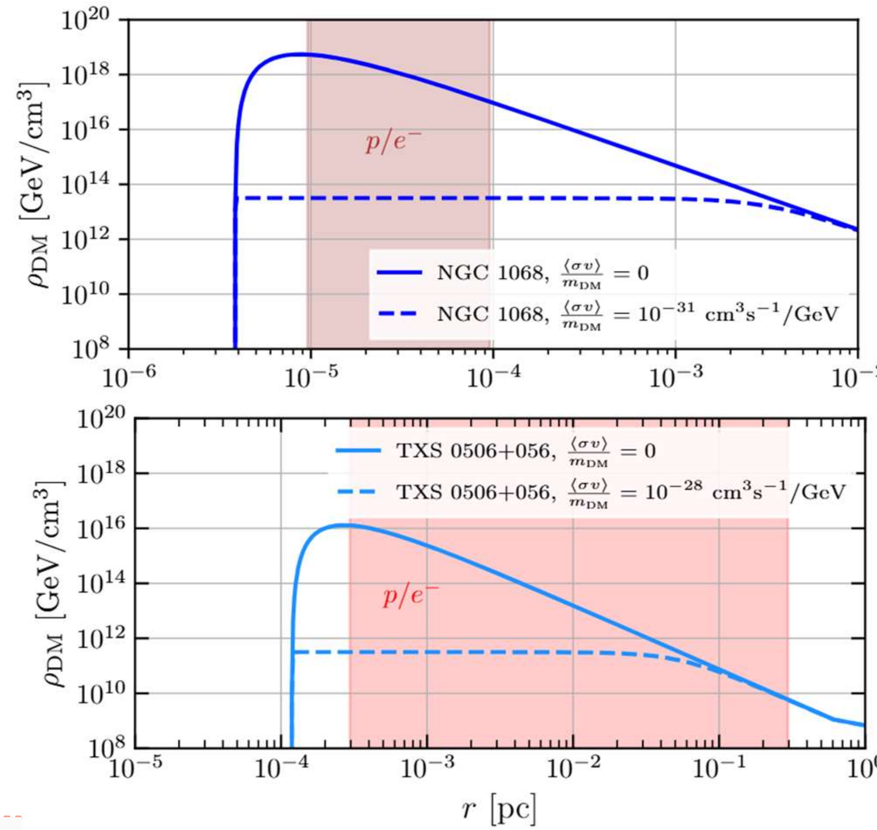
The DM around a SMBH can adiabatically form a spike with a much higher density than otherwise expected

$$\rho_{sp} = \rho_R g_\gamma(r)\left(R_{sp}/r\right)^{\gamma_{sp}}$$

Where $\gamma_{sp} = 7/3$ for an NFW profile. If annihilations are present, the density can only grow up to a maximum value

$$\rho_{sat} = \frac{m_{DM}}{\langle\sigma v\rangle t_{BH}}$$

([7] Herrera, Murase 2023)



Cosmic Ray Cooling

Can our current AGN observations constrain DM interactions?

Work in arXiv: 2408.08947

Big Idea – Cosmic Ray Cooling

If AGN cosmic rays would lose energy (cool) via scattering off DM particles. If this cooling is much faster than the rate predicted by the Standard Model, these cosmic rays would be unable to produce the neutrinos and gamma rays we observe.

$$\tau_{BSM} = \left(\frac{1}{E}\frac{dE}{dt}\right)^{-1}$$

We constrain BSM cooling so that

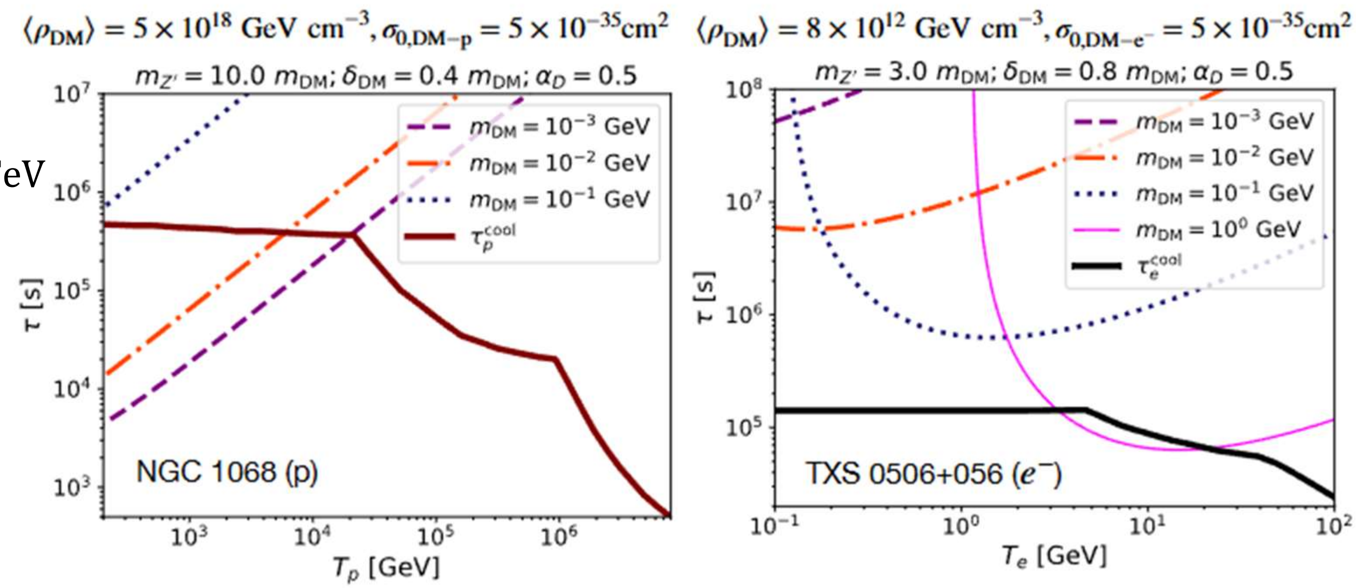
$$\tau_{BSM} \geq C\ \tau_{SM}$$

C = 0.1 for NGC 1068 and C = 1 for TXS 0506+056

$$\frac{dE}{dt} = -\frac{\langle \rho_{DM} \rangle}{m_\chi} \int dT_\chi \left(T_\chi + \delta\right) \frac{d\sigma}{dT_\chi}$$

Cooling Timescale

10 TeV < T_p < 300 TeV

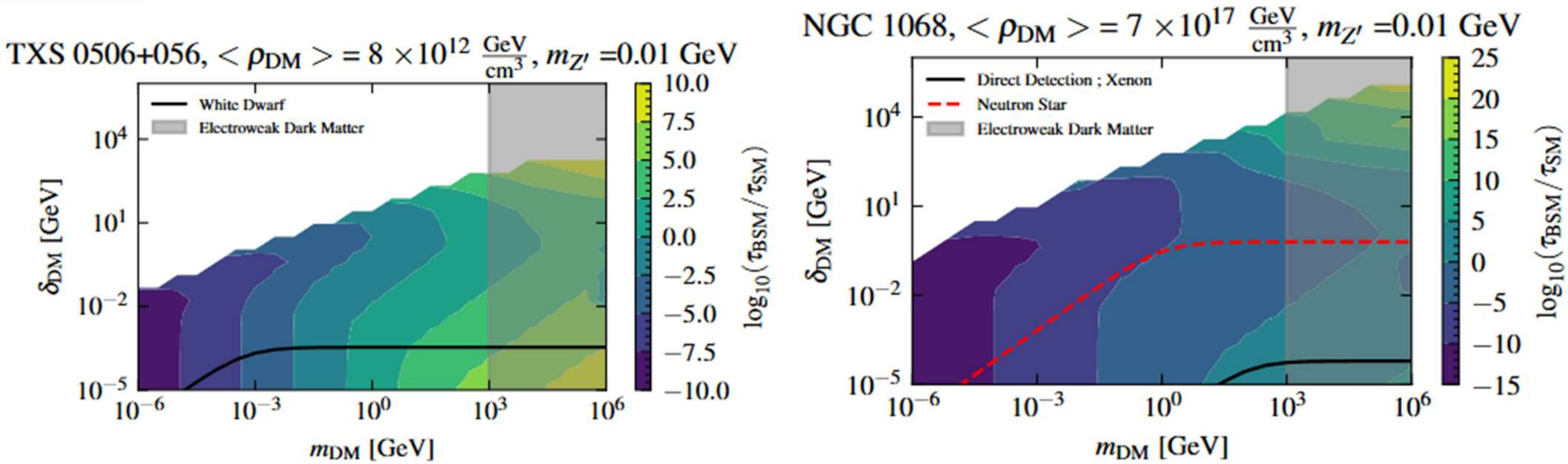


50 GeV < T_e < 2 TeV

For TXS, we can note the upturn in cooling times, around $T_e m_\chi \sim m_{Z'}^2$. This corresponds to where $q^2 > m_{Z'}^2$.

Cooling Rate Comparison

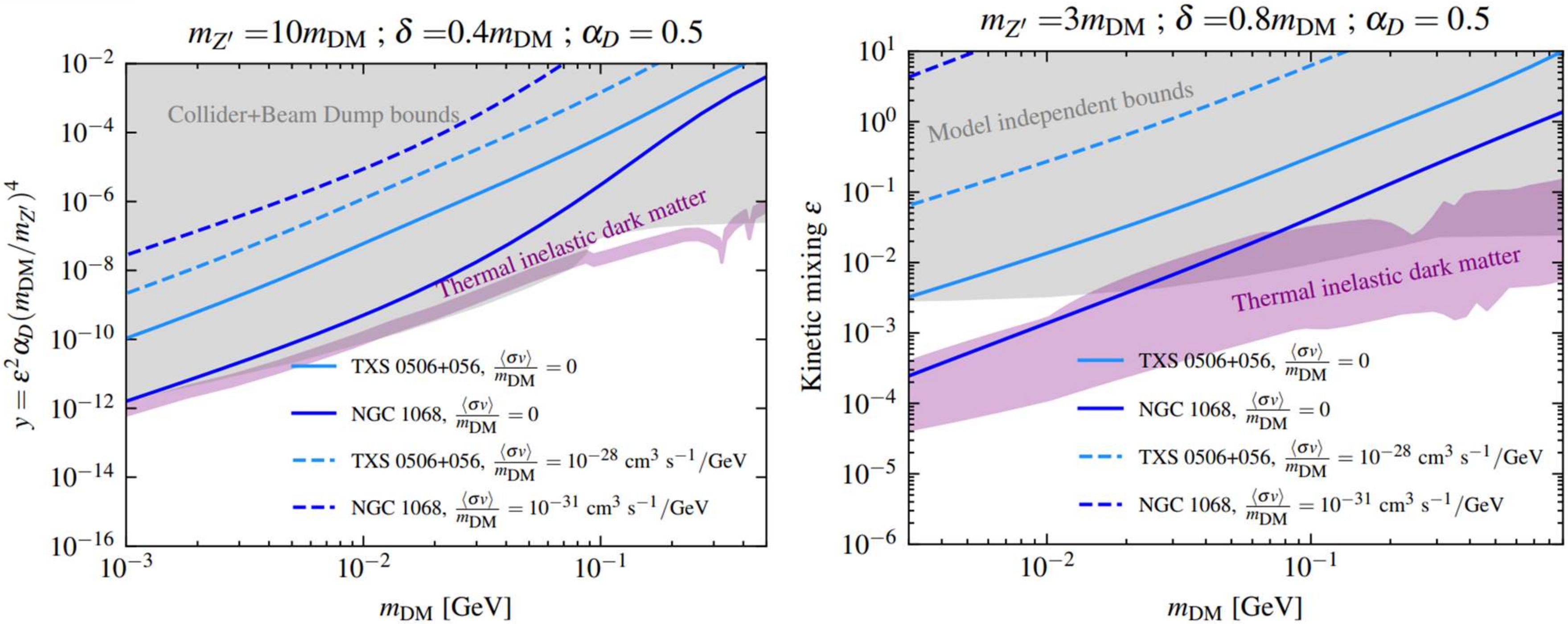
$g_\chi = g_{SM} = 1$



Note that from kinematics, we can only set constraints where $m_\chi > \frac{\delta^2 + 2m_{SM}\delta}{2T_{SM,max} - \delta}$

Also, bounds improve as δ increases, as this decreases $q^2 = 2m_\chi T_\chi - \delta^2$

Cooling Constraint w Existing Bounds



$$\epsilon = g_{SM}/e$$

Cooling Conclusions

Active Galactic Nuclei provide an efficient environment to search for indirect signals from DM due to the high energy of the cosmic rays and enhanced density from the DM spike

Looking for the over-cooling of cosmic rays in Active Galactic Nuclei can translate into constraints on inelastic DM with enormous mass splittings (up to TeV). Previously, these could only be constrained at colliders or through loop-diagrams.

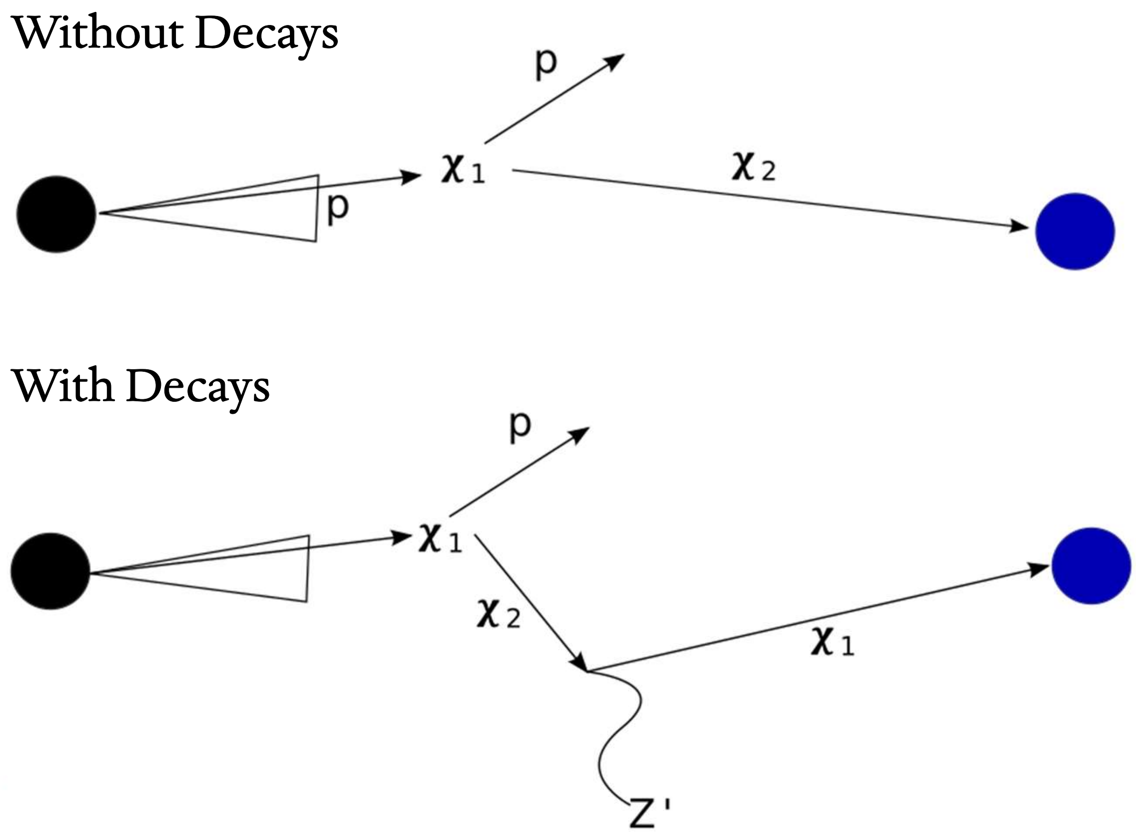
At low masses, this cooling argument can be used to set constraints near the values expected for thermal relic DM.

AGN Boosted Dark Matter

Can this energetic DM interact in terrestrial detectors?

Big Idea – Detection of Boosted DM

- After scattering with cosmic rays in the AGN, the DM may now have enough energy to scatter inelastically at direct detection and neutrino experiments.



Calculating the Flux of Dark Matter

Without considering decays, the flux of DM is computed as

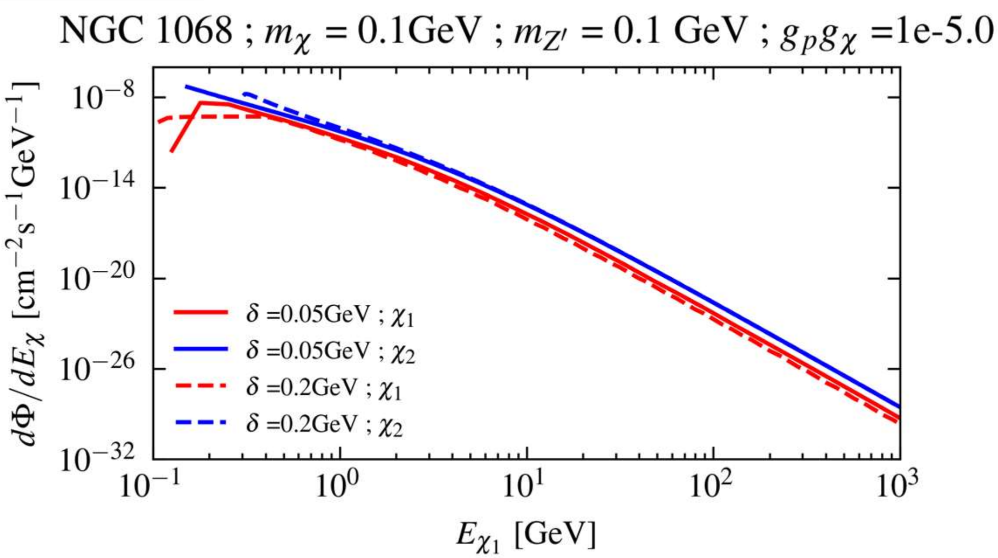
$$\frac{d\Phi_{\chi 2}}{dT_{\chi 2}} = \frac{\Sigma_\chi}{m_\chi d_{AGN}^2} \int dT_p \frac{d\sigma}{dT_{\chi 2}} \frac{d\Gamma_p}{dT_p d\Omega} \Big|_{cos\theta(T_p, T_{\chi 2})}$$

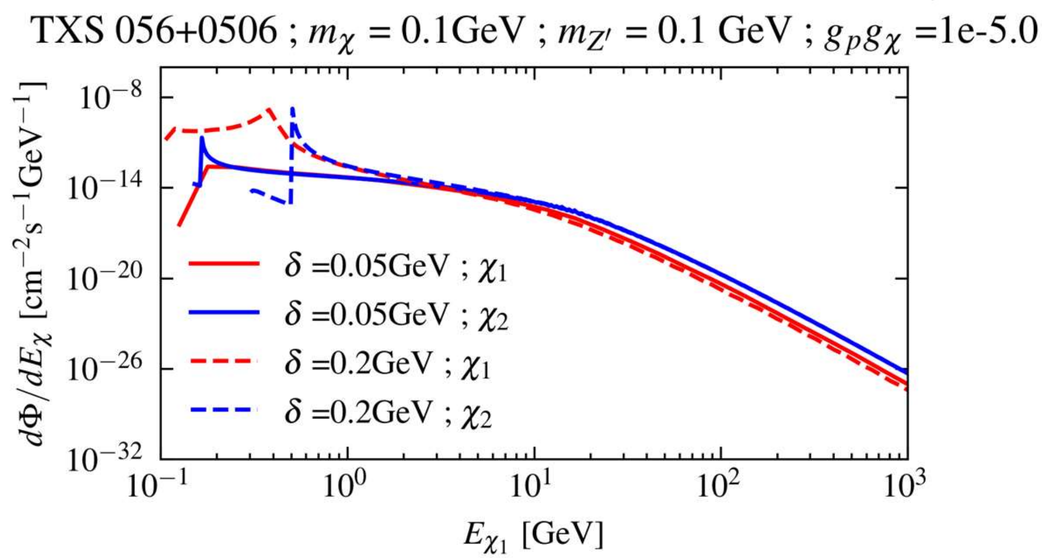
With the inclusion of decays, the flux is

$$\frac{d\Phi_{\chi 1}}{dT_{\chi 1}} = \frac{\Sigma_\chi}{4\pi m_\chi \, d_{AGN}^2} \int dT_p dT_{\chi 2} d\phi_s dE_{\chi 1,r} \frac{d\Gamma_p}{dT_p d\Omega} (\theta_p) \frac{d\sigma}{dT_{\chi 2}} \frac{1}{\Gamma_\chi} \frac{d\Gamma_\chi}{dE_{\chi 1,r}} \frac{1}{\gamma\beta p_r}$$

Σ_χ= integrated density ; ϕ_s is the azimuthal angle for scattering ; Γ_χ is the decay rate

Flux with and Without Decay





Interactions in Detectors

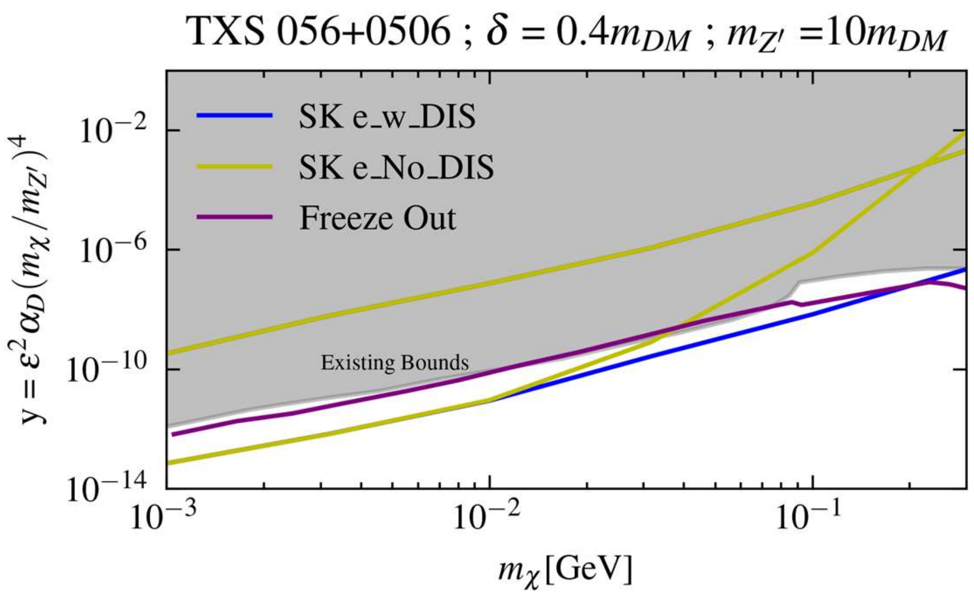
Super-K Run 4 has analyzed data looking for cosmic ray DM through scattering off of electrons. By applying angular and energy cuts, we can look for DM specifically from AGN.
This work has been done in the case of elastic DM.

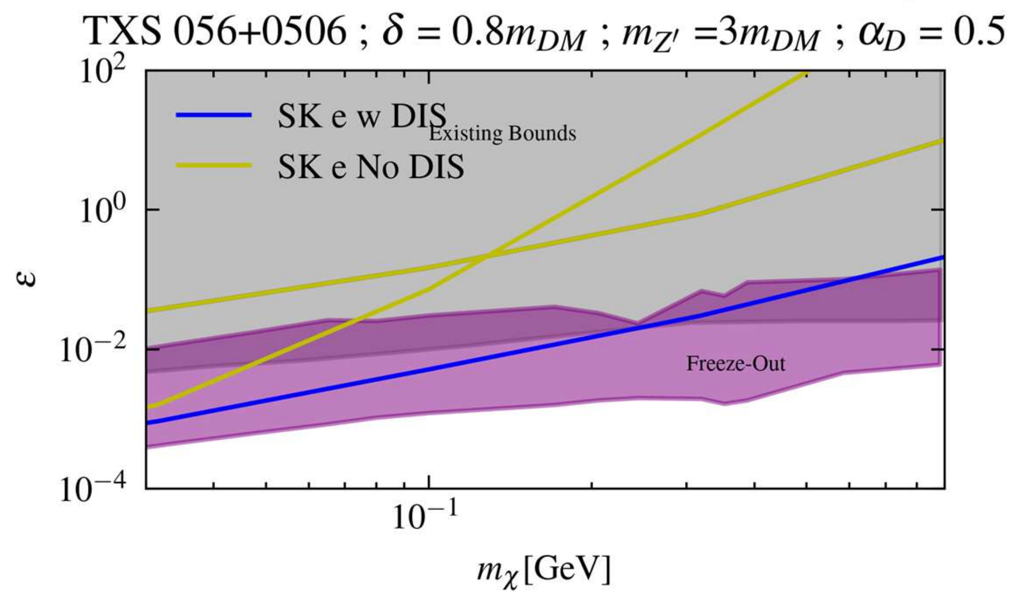
Sensitivity of Super-Kamiokande

	Bin1	Bin2	Bin3
T_e (GeV)	(0.1, 1.33)	(1.33, 20)	$(20,\ 10^3)$
N_{Data}	4042	658	3
N_{Bkg}	3992.9	772.6	7.4
ϵ_{sig}	93.0%	91.3%	81.1%
δ	24°	7°	5°
N^{δ}_{TXS}	169	2	0
N^{δ}_{BL}	167	4	0
N^{δ}_{Bkg}	172.6	2.88	0.014
N_{TXS} (95% C.L.)	19.39	3.42	2.98
N_{BL} (95% C.L.)	17.27	6.27	2.98

([8] Wang, Granelli, Ullio 2022)

Preliminary Constraints





AGN Boosted Inelastic DM Conclusions

AGN cosmic rays can scatter of inelastic DM with large mass splittings. These DM particles obtain sizable kinetic energies.

Even after decay, these DM particles may still have enough energy to scatter in terrestrial detectors.

Existing analyses of Super-K allow for us to probe thermal inelastic DM parameter space. Future work considering Xenon, Icecube, etc. will hopefully expand this coverage.

Thank you!

Any Questions?

References

[1] Carter Hall. Generation 3 dark matter searches, axions, and direct detection of dark matter. PHENO-DPF Conference May 15, 2024. Pittsburg USA.
[2]J. Acevedo et al. "Neutrino and Gamma-Ray Signatures of Inelastic Dark Matter Annihilating outside Neutron Stars." arXiv preprint arXiv:2404.10039 (2024).
[3]M. Mongillo, et al. Constraining light thermal inelastic dark matter with NA64. The European Physical Journal C 83.5 (2023): 391.
[4] R. Abbasi et al. ,Evidence for neutrino emission from the nearby active galaxy NGC 1068.Science378,538-543(2022).DOI:10.1126/science.abg3395
[5] W. Winter, et al. Multi-messenger interpretation of the neutrinos from TXS 0506+ 056. PoS (ICRC2019) 1032. arXiv preprint arXiv:1909.06289 (2019).
[6] K. Murase. Hidden hearts of neutrino active galaxies. The Astrophysical Journal Letters 941.1 (2022): L17.
[7]G. Herrera and K. Murase. Probing light dark matter through cosmic-ray cooling in active galactic nuclei. Physical Review D 110.1 (2024): L011701.
[8]A. Granelli, P. Ullio, and J. Wang. "Blazar-boosted dark matter at Super-Kamiokande." Journal of Cosmology and Astroparticle Physics 2022.07 (2022): 013.

Bonus Slides

Cross Section

It is helpful to characterize cosmic ray scattering in terms of $s = E_{com}^2$

$$s = (m_{SM} + m_\chi)^2 + 2T_{SM}m_\chi$$

The momentum transfer q

$$q^2 = 2T_\chi m_\chi - \delta^2$$

The non-relativistic characteristic cross section

$$\sigma_0 = \frac{g_{SM}^2 g_\chi^2 \mu_{DM-S}^2}{\pi\, m_{Z'}^4}$$

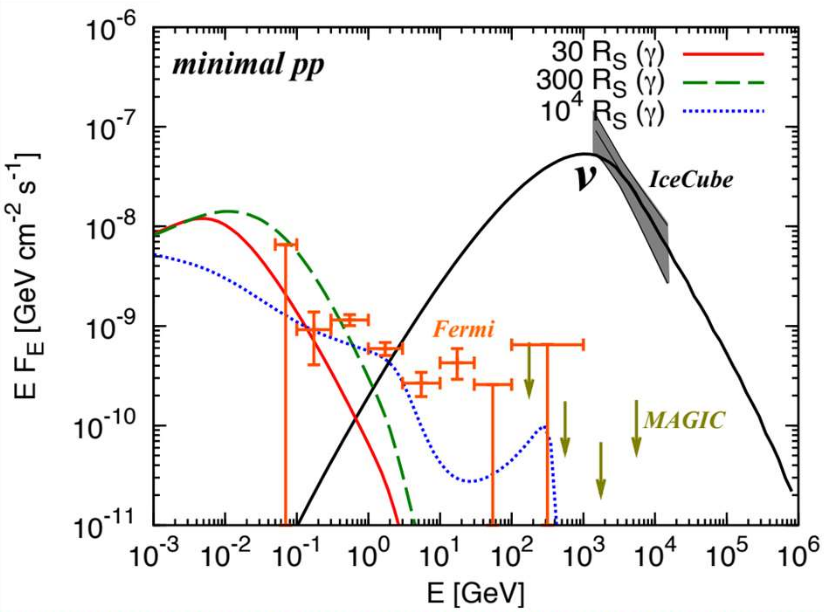
Then we can obtain the full differential cross section

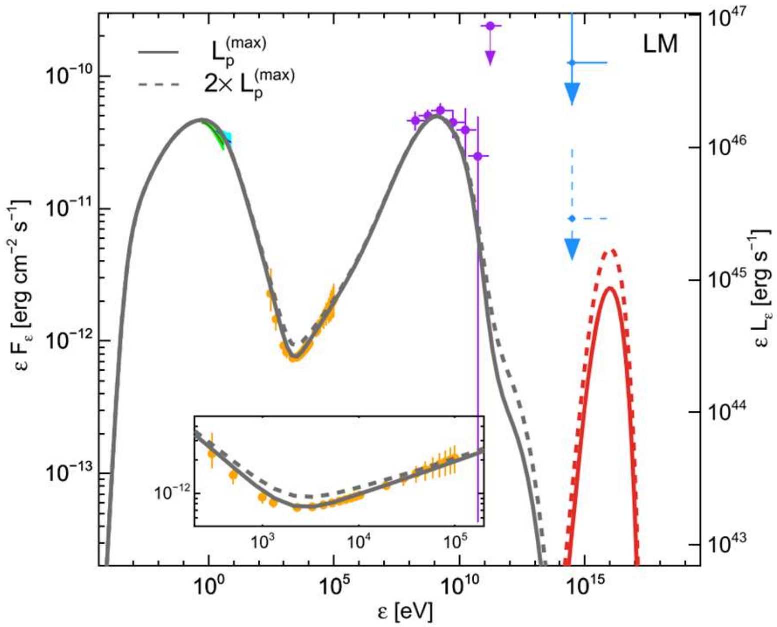
$$\frac{d\sigma}{dT_\chi} = \sigma_0 \frac{m_{Z'}^4}{(m_{Z'}^2 + q^2)^2} \frac{m_\chi \left[\left(s - (m_\chi^2 + m_{SM}^2 + \delta\, m_\chi)\right)^2 + m_\chi T_\chi (q^2 - 2s)\right]}{2\, \mu_{\chi-SM}^2 \lambda(m_\chi^2, m_{SM}^2, s)} F_{SM}(q^2)$$

Where $F_{SM}(q^2)$ is the form factor. In this work, we don't consider scattering off quarks or nuclear excitations.

AGN Multimessenger Modeling

The observed neutrinos and photons are secondary particles in the AGN. From the observations, we can infer models of the initial charged particle spectrum, along with energy loss (cooling) rates.

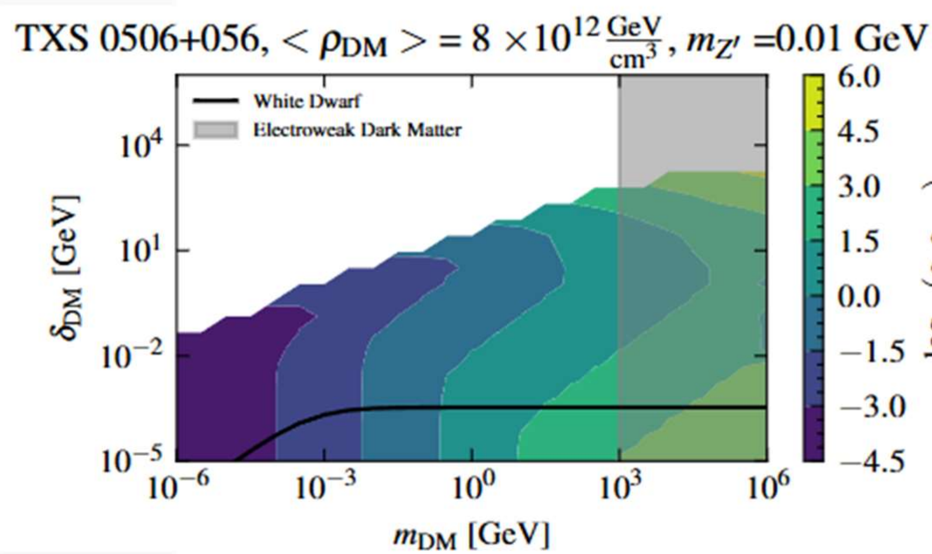


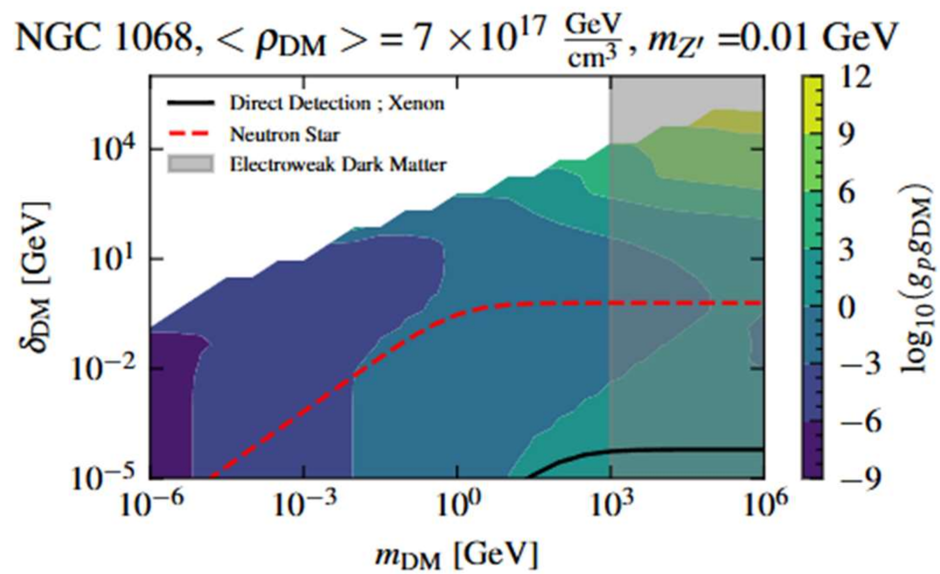


NGC 1068
([7] Murase 2022)

TXS 0506+056
([8] Keivani et al. 2018)

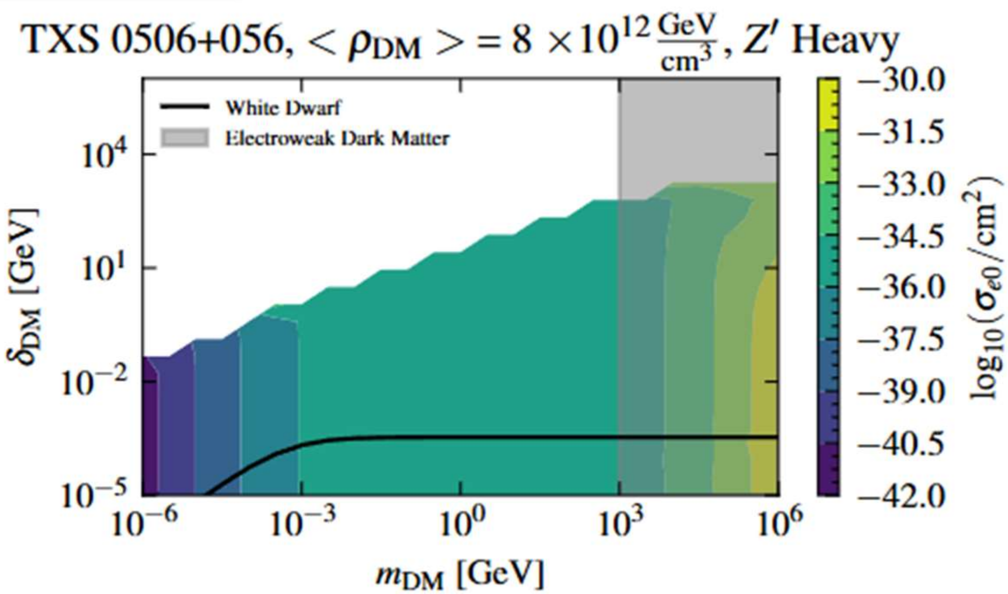
Coupling Limits

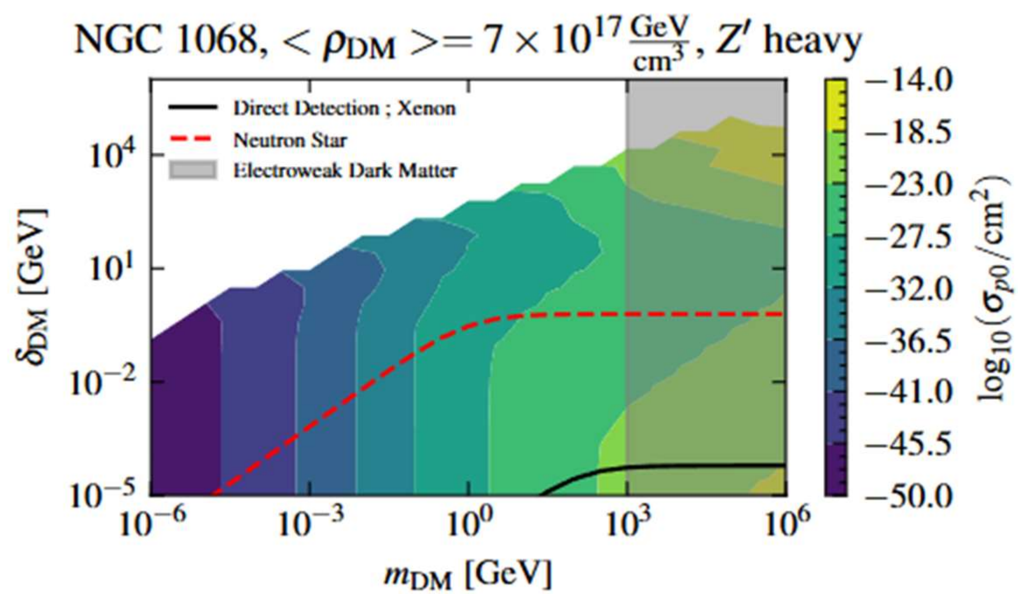




These coupling limits are obtained from the cooling times, by saying that cross section goes as the product of coupling squared. This breaks down at higher couplings, as it becomes non-perturbative, so care needs to be taken in addressing the physicality of these limits.

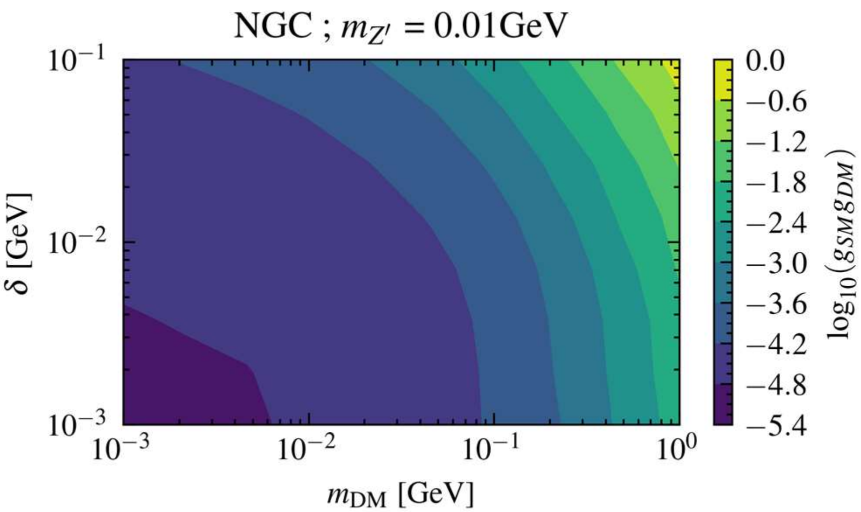
Cross Section Limits for Heavy Mediators

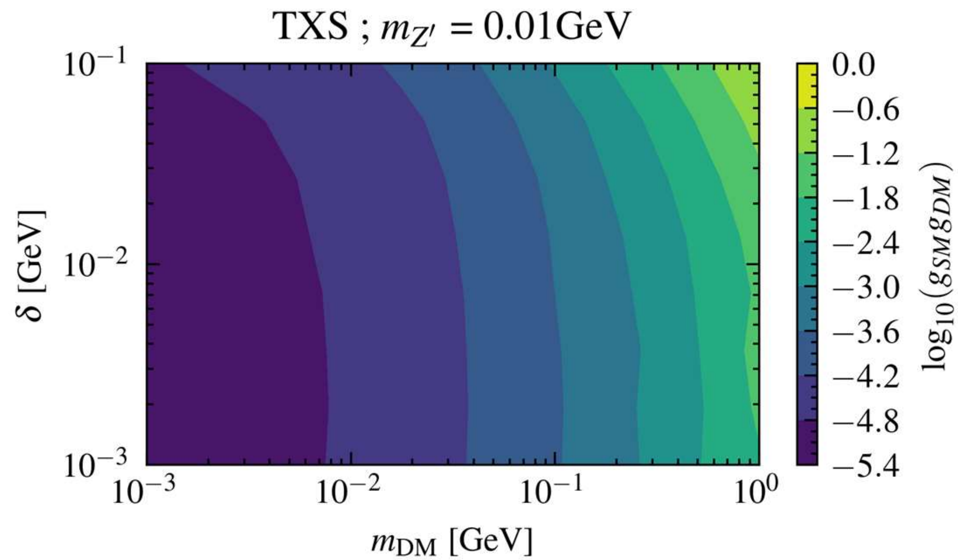




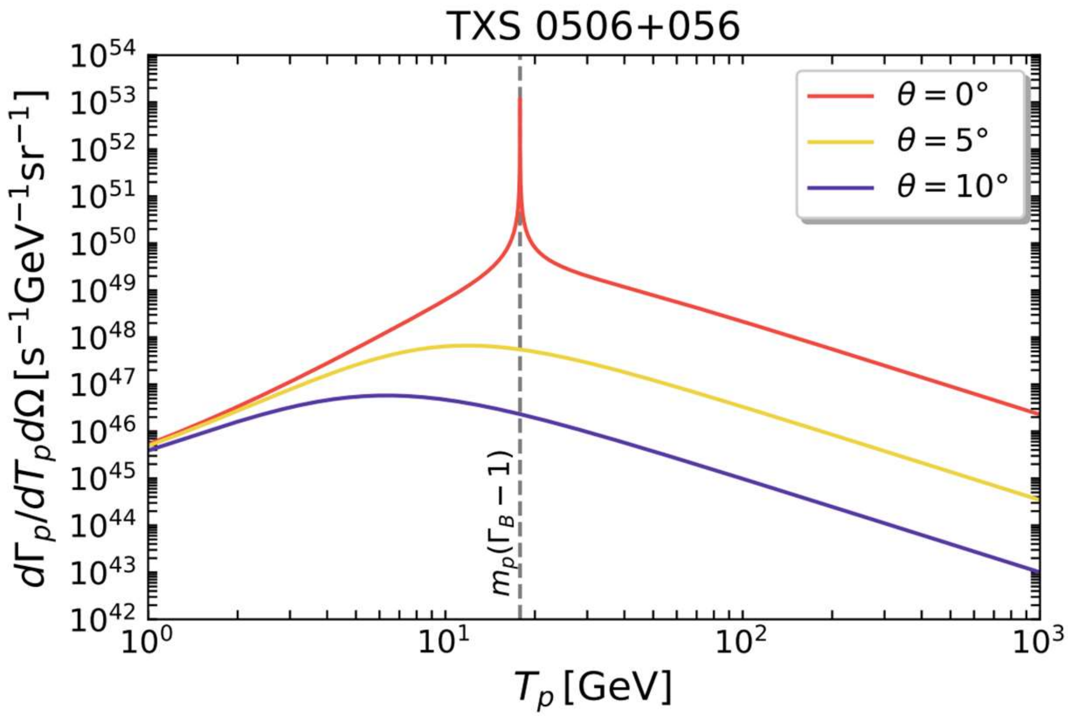
"Heavy" implies $m_{Z'}^2 \gg q^2$ for all relevant energies

Preliminary Constraints - Boosting





Model of AGN Jet



([10] Wang, Granelli, Ullio 2022)

In the frame of a "blob" the energy follows

$$\frac{d\Gamma_p'}{dE_p' d\Omega'} = \frac{1}{4\pi} c_p \left(\frac{E_p'}{m_p}\right)^{-\alpha_p}$$

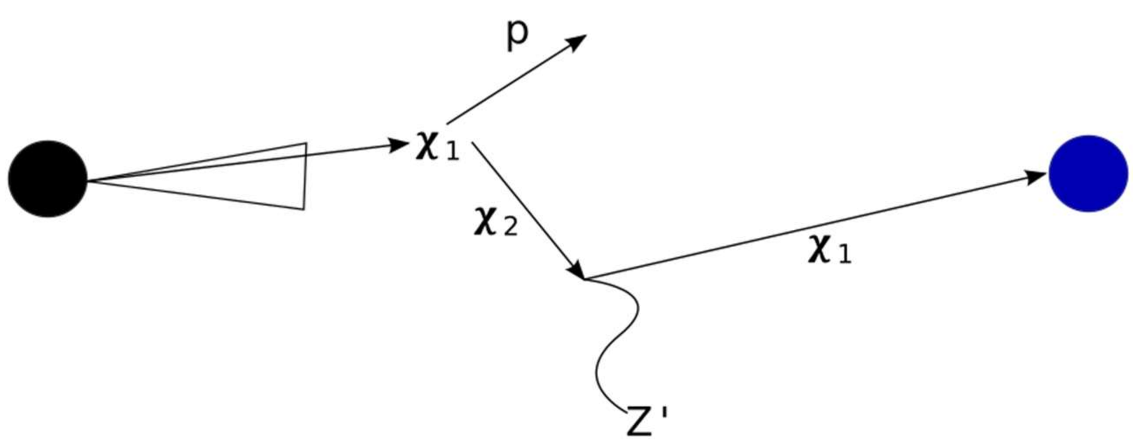
If the blob has boost factor Γ_B, then the energy distribution is

$$\frac{d\Gamma_p}{dE_p d\Omega} = \frac{c_p}{4\pi}\left(\frac{E_p}{m_p}\right)^{-\alpha_p} \frac{\beta_p (1 - \beta_p \beta_B \mu)^{-\alpha_p} \Gamma_B^{-\alpha_p}}{\sqrt{(1 - \beta_p \beta_B \mu)^2 - (1 - \beta_p^2)(1 - \beta_B^2)}}$$

For TXS 0506+056, $\Gamma_B = 20$
For NGC 1068 $\Gamma_B = 1$ (no jet)

Decays of χ_2

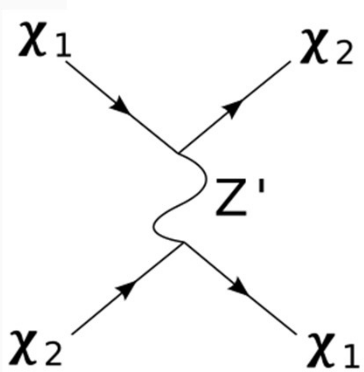
$$\chi_2 \rightarrow \begin{cases} \chi_1 + \gamma \text{ if } \delta < m_{Z'} \text{ and } \delta < 2\, m_e \text{ (monoenergetic)} \\ \chi_1 + e^+ + e^- \text{ if } \delta < m_{Z'} \text{ and } \delta > 2 m_e \text{ (distribution)} \\ \chi_1 + Z' \text{ if } \delta > m_{Z'} \text{ (monoenergetic)} \end{cases}$$



Self-Interactions

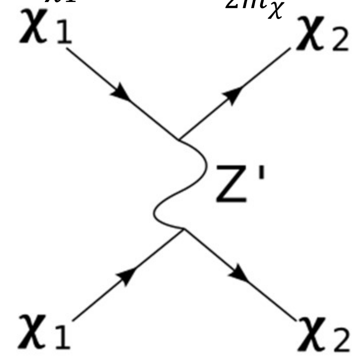
When the coupling of DM to the new mediator becomes large, we might have to worry about self-scattering. This will modify the spectrum from the AGN

No Kinematic Limit



Only possible when

$T_{\chi_1} > 4\delta + \frac{\delta^2}{2m_\chi}$



Time

Simplifying Assumptions for Self-Scattering

- The AGN proton flux is unaffected
- The DM does not decay in the spike
- All scattering is colinear
- We only consider a very heavy vector mediator

Calculating Self Scattering

To compute the differential flux of DM a distance x from the starting location, we must calculate the differential equations

$$\frac{m_\chi}{\rho}\frac{d}{dx}\frac{dN_1}{dE_1} = -\sigma_1(E_1)\frac{dN_1}{dE_1} + \int dE_2' \frac{d\sigma(E_2')}{dE_1}\frac{dN_2}{dE_2'} \longleftarrow (\chi_1 + \chi_2 \rightarrow \chi_1 + \chi_2)$$

$$\frac{m_\chi}{\rho}\frac{d}{dx}\frac{dN_2}{dE_2} = -\sigma_2(E_2)\frac{dN_2}{dE_2}$$

$$+\left(\int dE_{SM}\frac{d\sigma(E_{SM})}{dE_2}\frac{dN_{SM}}{dE_{SM}}\right) + \left(\int dE_2' \frac{d\sigma(E_2')}{dE_2}\frac{dN_2}{dE_2'}\right) + 2\left(\int dE_2' \frac{d\sigma(E_1')}{dE_2}\frac{dN_1}{dE_1'}\right)$$

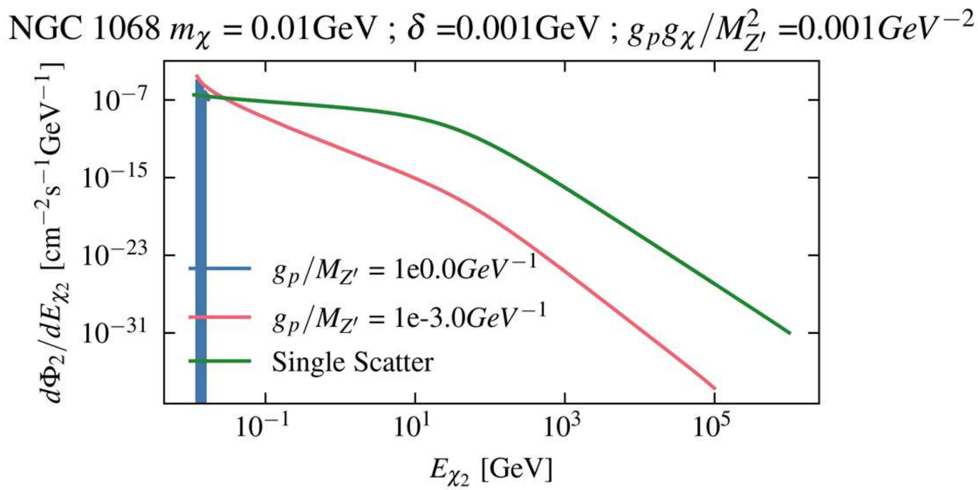
$(\chi_1 + SM \rightarrow \chi_2 + SM)$ $(\chi_1 + \chi_2 \rightarrow \chi_1 + \chi_2)$ $(\chi_1 + \chi_1 \rightarrow \chi_2 + \chi_2)$

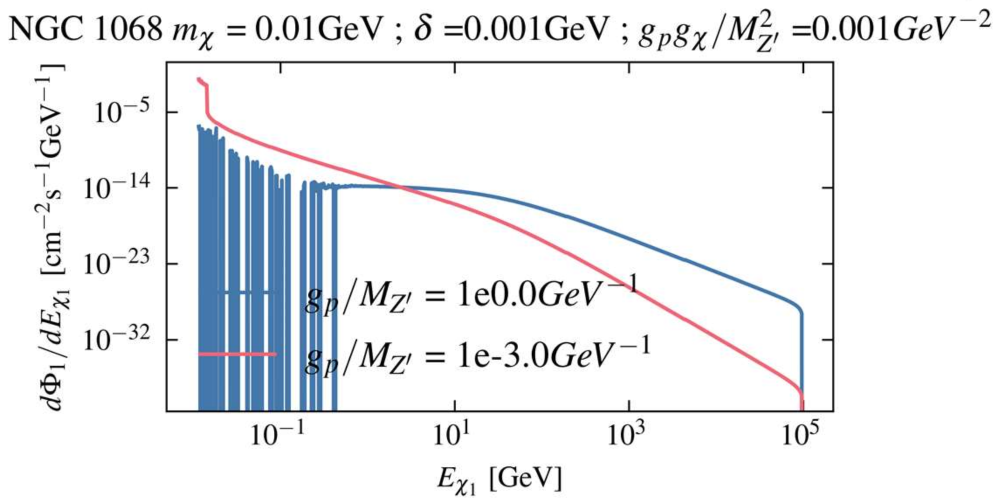
Calculating Self Scattering

If we discretize the flux into a finite number of energies, then this problem is just a matrix equation, which can be determined by computing the eigensystem of

$$\frac{m_{DM}}{\rho}\frac{d}{dx}\begin{pmatrix} dN_1/dE_1 \\ dN_2/dE_2 \\ dN_{SM}/dE_{SM} \end{pmatrix} = \begin{pmatrix} -\sigma_1 & dE_2 \times \frac{d\sigma_2}{dE1} & 0 \\ 2dE_1 \times \frac{d\sigma_1}{dE_2} & dE_2' \times \frac{d\sigma_2}{dE_2} - \sigma_2 & dE_{SM} \times \frac{d\sigma_{SM}}{dE_2} \\ 0 & 0 & 0 \end{pmatrix}\begin{pmatrix} dN_1/dE_1 \\ dN_2/dE_2 \\ dN_{SM}/dE_{SM} \end{pmatrix}$$

Self-Interactions Flux Consequences





Increasing g_χ while keeping $g_\chi g_{SM}$ fixed will lead to a suppressed flux at high energies, and an enhanced flux at low energies.

There is a pile-up of χ_1 when they no longer have the energy to scatter $T_{thesh} = 4\delta + \frac{\delta^2}{2m_\chi}$

Self-Interactions Conclusions

Self-Interactions remove the degeneracy of g_{SM} and g_{χ}, making this a 5-variable problem

$$m_{DM} \; ; \; \delta \; ; \; m_{Z'} \; ; \; g_{\chi} \; ; \; g_{SM}$$

We save a full analysis of this problem for later; in the meantime, it is good to consider a few important questions

1) Would self-interactions substantially change my flux of DM?
2) Could this alter the distribution of DM around the AGN?
3) What other observables could this involve?

Example of Inelastic Dark Matter

From (Garcia, Kahlhoefer, Ovchynnikov, Schwetz 2024)

Introduce states χ_L, χ_R, S which are singlets in the SM, but charged under a new U(1) symmetry (the fermions have equal charge). The additions to the Lagrangian are

$$\mathcal{L}_\chi = i\bar{\chi}_L \not{D} \chi_L + i\bar{\chi}_R \not{D} \chi_R - m_D^* \bar{\chi}_L \chi_R - \sqrt{2} y_L S \bar{\chi}_L^c \chi_L - \sqrt{2} y_R S \bar{\chi}_R^c \chi_R + \text{h.c.}\,,$$
$$\mathcal{L}_V = -\frac{1}{4} A'^{\mu\nu} A'_{\mu\nu} - \frac{1}{2} \frac{\epsilon}{\cos\theta_w} B^{\mu\nu} A'_{\mu\nu}\,,$$
$$\mathcal{L}_S = (D^\mu S)^* (D_\mu S) + \mu_s^2 |S|^2 - \lambda_s |S|^4 - \lambda_{hs} |S|^2 |H|^2\,,$$

Let S obtain a vev w, then one can redefine the fermions to have mass

$$m_{\chi^{(*)}} = \sqrt{m_d^2 + w^2 (y_R - y_L)^2} \mp w (y_L + y_R)\,.$$

Condition for Adiabatic Spike Formation

We wish to compare the dynamical time t_{dyn} with the Salpeter timescale t_{sal}.

$$t_{dyn} = GM_{BH}/\sigma_v^3$$

where σ_v is the velocity dispersion for stars outside the BH's radius of influence

$$t_{sal} = M_{BH}/\dot{M_{edd}}$$

where $\dot{M_{edd}}$ refers to Eddington accretion.

SM Cooling Mechanisms

For protons in NGC 1068, the primary cooling mechanisms are:

proton-proton interactions for $T_p \leq 10^4$GeV

proton-photon interactions for $10^4 < T_p \leq 10^6$GeV

Bethe-Heitler ($p + \gamma \rightarrow p + e^+ + e^-$) for $T_p > 10^6$GeV

For electrons in TXS 0506+056

escape losses for $T_e < 5$ GeV

inverse Compton scattering for 5 GeV $< T_e < 40$ GeV

synchrotron radiation for $T_e > 40$ GeV

Acceleration Mechanisms and Locations

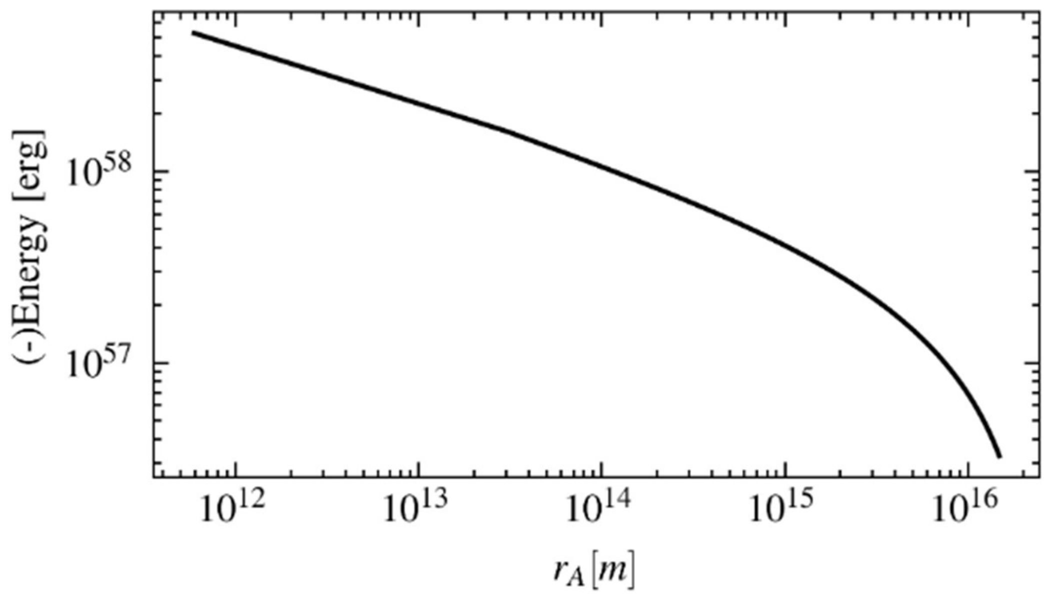
Possible acceleration mechanisms are shocks, turbulence, and magnetic reconnection.

Possible acceleration locations are at the disk-coronae and jets.

While TXS 0506+056 has a jet, NGC 1068 does not.

Altering A Spike

$$\rho_{\rm DM}(r) = \begin{cases} 0 \quad \text{for} \quad r < 4R_s \\ \rho_0 R_{sp}^{7/3} r_A^{-7/3} \quad \text{for} \quad 4R_s < r < r_A \\ \rho_0 R_{sp}^{7/3} r^{-7/3} \quad \text{for} \quad r_A < r < 10^5 R_s \end{cases}$$



Here we show the energy in the SMBH-DM spike system as a function of a core around the SMBH. Typical AGN energies are ~ 10^{49} erg/s, so spikes may be disrupted if a sizable fraction of the energy goes in.

Bonus References

[]Garcia, Giovani Dalla Valle, et al. "Not-so-inelastic Dark Matter." *arXiv preprint arXiv:2405.08081* (2024).